RESEARCH DEPARTMENT

COLOUR TELEVISION:

THE ADAPTATION OF THE N.T.S.C. SYSTEM TO U.K. STANDARDS

PART I: THE COLORIMETRY OF ANALYSIS AND SYNTHESIS

Report No. T-060/1

(1956/30)

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SUMMARY

The mathematical transformations involved in specifying the ideal analysis filters for a colour scanner are described using the notation of classical matrix algebra. The colorimetric performance of an actual scanner is evaluated in terms of MacAdam's just noticeable differences. An electrical matrixing method is described which results in some improvement in colour rendering accuracy, but at the cost of reduction in the signal-to-noise ratio of the picture.

1. INTRODUCTION.

In adapting the N.T.S.C. colour television system to U.K. standards, a thorough investigation of the practical implications of three-colour analysis and synthesis was undertaken so that the system should be operating as near as possible to the ideal requirements. The principles of three-colour analysis have been described in the literature many times[1-3]: this report will give a very brief resumé of these principles using matrix algebra for the mathematical transformations involved. The purpose of the report is concerned with the attempt to apply the principles to a specific example of colour scanner[4], and the accuracy of colour reproduction which results. MacAdam's[5] values for just noticeable colour differences are used in assessing the errors in colour reproduction.

2. ANALYSIS REQUIREMENTS.

It is necessary at the outset to know the chromaticities of the colours which are to be used in the display device. The chromaticities of the phosphors for the N.T.S.C. system have been standardised[6] as follows:

TABLE 1

Primary Colours	Chromaticity Co-ordinate		
	x	y	z
Red	0·67	0·33	0·00
Green	0·21	0·71	0·08
Blue	0·14	0·08	0·78

The usual procedure involved in the calculation of the sensitivity curves for colour analysis requires that a white be specified so that we can determine how much of each colour (in lumens) is needed to produce the specified white. The corresponding three unknowns (a, b, c) are determined from the following matrix equation:

$$\begin{bmatrix} 0\cdot67 & 0\cdot21 & 0\cdot14 \\ 0\cdot33 & 0\cdot71 & 0\cdot08 \\ 0\cdot00 & 0\cdot08 & 0\cdot78 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0\cdot310 \\ 0\cdot316 \\ 0\cdot374 \end{bmatrix} \tag{1}$$

The chromaticity co-ordinates on the right-hand side of Equation (1) are those of Illuminant C, which is the white which has been chosen in the U.S.A. for the N.T.S.C. system, although with some adverse comment from MacAdam[7] and Sproson[8]. This equation expresses the fact that the magnitude of the x chromaticity co-ordinate of Illuminant C can be found by adding 'a' units of the x chromaticity co-ordinate of the red, 'b' units of the x co-ordinate of the green and 'c' units of the blue, and similarly for the y and z co-ordinates of Illuminant C. The method of calculation does not, however, depend in any way on the exact white point chosen, and so Illuminant C will be used in this report.

The solution of Equation (1) gives

$$a = 0\cdot286$$

$$b = 0\cdot261$$

$$c = 0\cdot453$$

Substituting these values into Equation (1) we obtain

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0\cdot192 & 0\cdot055 & 0\cdot063 \\ 0\cdot094 & 0\cdot185 & 0\cdot036 \\ 0\cdot000 & 0\cdot021 & 0\cdot353 \end{bmatrix} \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix} \tag{2}$$

For R = G = B = 1, $Y = 0\cdot315$, i.e. the luminance component. Multiplying by

$$\frac{1}{0\cdot315},$$

we obtain a normalised matrix in the sense that $Y = 1$ when R = G = B = 1.

Thus

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0\cdot607 & 0\cdot174 & 0\cdot200 \\ 0\cdot299 & 0\cdot587 & 0\cdot114 \\ 0\cdot000 & 0\cdot066 & 1\cdot116 \end{bmatrix} \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix} \tag{3}$$

The luminance component Y is frequently written as

$$0{\cdot}30\mathrm{R} + 0{\cdot}59\mathrm{G} + 0{\cdot}11\mathrm{B}$$

the coefficients of which correspond to the middle line of the square matrix in (3), approximated to two figures.

If X, Y, Z take the tristimulus values of the spectrum colours, we can then determine for each wavelength how much R, G and B are required (trichromatic units).

The required expression is given by

$$\begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix} = \begin{bmatrix} 1{\cdot}910 & -0{\cdot}532 & -0{\cdot}288 \\ -0{\cdot}985 & 1{\cdot}999 & -0{\cdot}028 \\ 0{\cdot}058 & -0{\cdot}118 & 0{\cdot}898 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{4}$$

which is the reciprocal relation to (3).

Upon substituting the known values[9] of the distribution coefficients of the spectrum locus for an equi-energy stimulus, the sensitivity curves are obtained which give the spectral responses required by the red, green and blue channels of a colour camera or colour telecine machine for correct colour reproduction on a display device having the stated chromaticities. The result of this calculation is shown in Fig. 1.

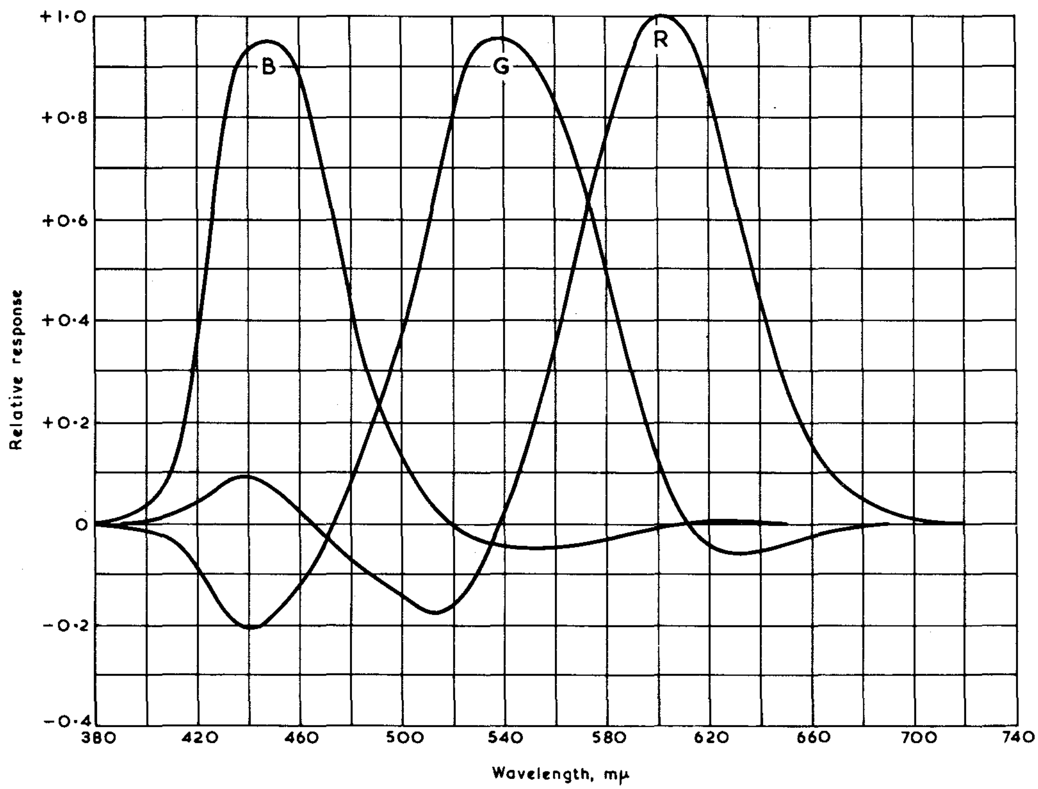

Fig. 1 - Ideal analysis curves for the N.T.S.C. primaries

It will be observed that each curve has a major positive portion, with two subsidiary lobes which may be either positive or negative. The effect of making changes in the chromaticities of the primary colours (always provided that they remain red, green and blue) is to cause relatively little change in the positions of the major peaks of the sensitivity curves and to cause considerable changes in the secondary positive or negative lobes. This explains why tolerably good colour reproduction can be obtained in a colour television or colour photographic system without critical attention being paid to the exact shape of the R, G, B spectral responses of the system. Nevertheless, if the best reproduction is being sought, proper attention must be directed to obtaining the correct spectral sensitivities.

3. THE SPECTRAL RESPONSE OF A COLOUR-FILM SCANNER.

The optical elements of a flying-spot colour-film scanner are shown in Fig. 2.

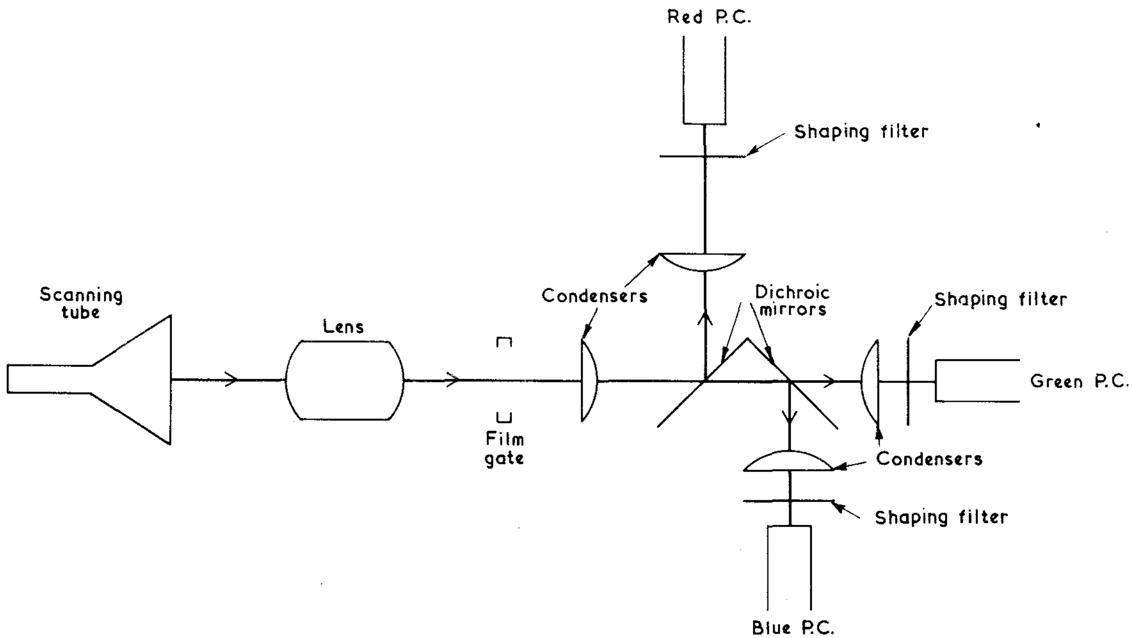

Fig. 2 - Optical elements of a film scanner

The elements which control the colour response are:

1. The flying-spot scanning tube
2. The dichroic mirrors
3. The shaping filters
4. The photocells.

It is desirable that the products of the spectral responses of these four elements shall closely approximate to the major positive portions of the mixture curves shown in Fig. 1. The only available scanning tube with a sufficiently short afterglow

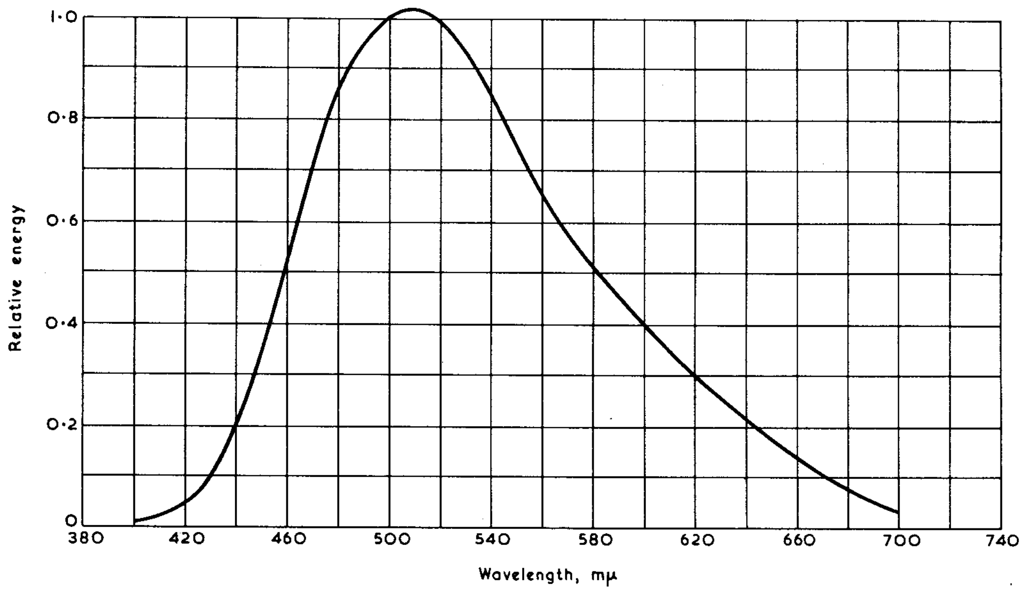

Fig. 3 - Measured spectral emissivity of zinc oxide phosphor

and a reasonably broad-band spectral emission is one using zinc oxide as phosphor. The spectral emissivity of this is shown in Fig. 3. The dichroic mirror assembly splits the luminous flux from this source into its red, green and blue components. The characteristics of the mirrors are chosen so as to require the least possible modification by the shaping filters. Ideally, the dichroic mirrors would have characteristics which eliminated the need for shaping filters, but this is not possible in practice.

Of the various photocells commercially available, only a few have suitable spectral responses for a colour scanner: Fig. 4 shows both the blue-sensitive type

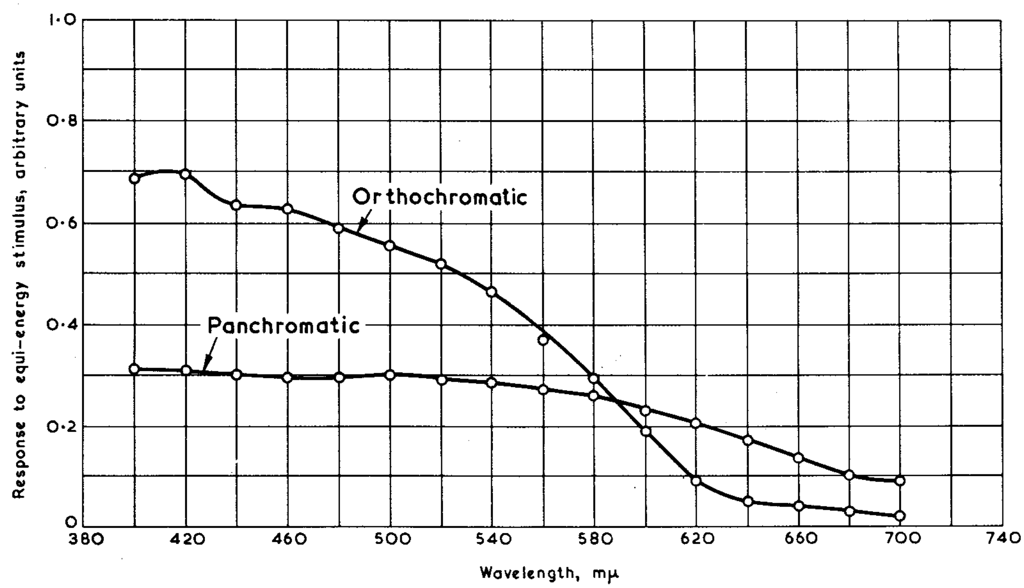

Fig. 4 - Measured spectral sensitivities of orthochromatic and panchromatic photocells
Types RCA 5819 and 6217

which can be used in the blue or green channel, and the panchromatic version which is the best that is available for the red channel. It will thus be seen that there is at present no choice in the flying-spot scanning tube, and very restricted choice in the matter of the photocells. The dichroic mirrors can be designed to meet specific requirements because their characteristics are controllable by the number of layers, the materials used and the thickness of the deposits[10]. The optimum characteristics are almost achieved in the Fish-Schurman Types 32 and 35, the transmission curves of which are shown in Fig. 5. The combination of cathode-ray tube, photocells,

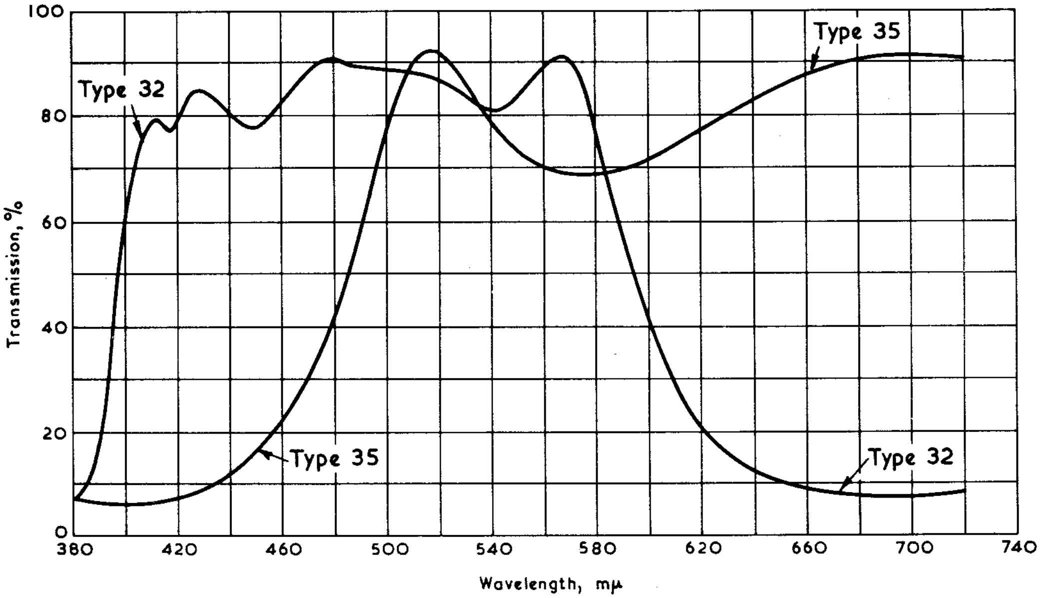

Fig. 5 - Spectral transmission characteristics of two dichroic mirrors measured at 45° incidence (Fish Schurman types 32 and 35)

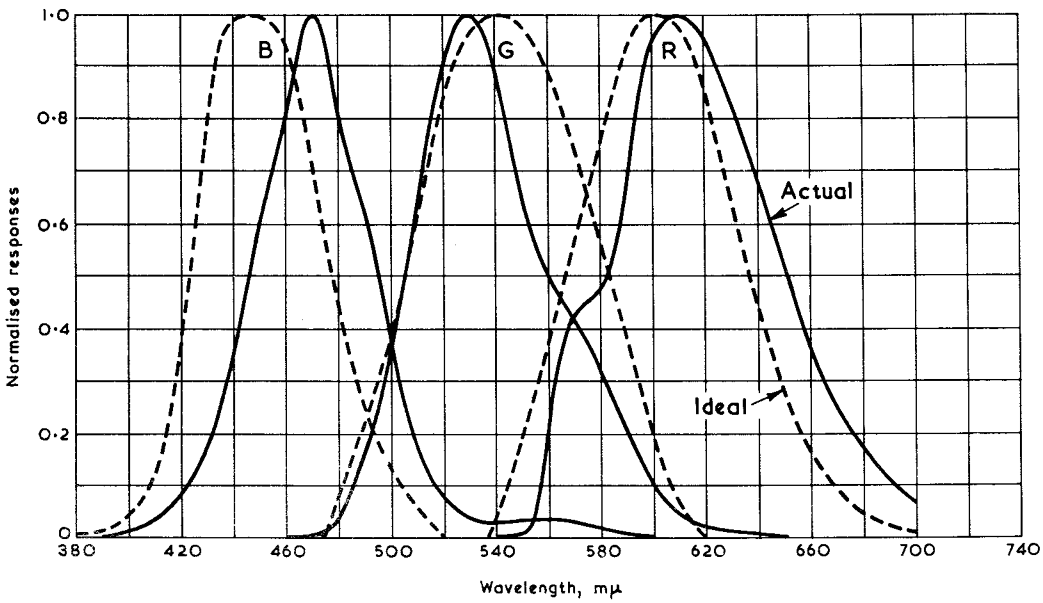

Fig. 6 - Comparison of ideal spectral responses with those obtained by the use of shaping filters

dichroic mirrors and shaping filters gives rise to spectral responses shown in Fig. 6. These are compared with the ideal responses* shown as dotted lines in the diagram.

4. ASSESSMENT OF ERRORS.

The question which arises on account of the impossibility of accurately producing even the positive portions of the mixture curves (Fig. 1) is: "How serious are the errors in colour reproduction?" For this purpose the reproduction of six fully-saturated and six desaturated colour filters was calculated. The television system assumed for the calculation consisted of the colour scanner and a display device having phosphor chromaticities in accordance with Table 1. The calculation is simple in principle and amounts to multiplying each of the curves of Fig. 6 by the spectral transmission of the filter in question and evaluating the areas, which are proportional to the outputs from the photocells. These three outputs (R, G and B)** are then applied to the tricolour kinescope or other display device and the final colour is given by matrix 3:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{\cdot}607 & 0{\cdot}174 & 0{\cdot}200 \\ 0{\cdot}299 & 0{\cdot}587 & 0{\cdot}114 \\ 0{\cdot}000 & 0{\cdot}066 & 1{\cdot}116 \end{bmatrix} \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{bmatrix} \qquad (3)$$

where X, Y, Z are the tristimulus values of the reproduced colours, and the chromaticity co-ordinates (x, y, z) are the normalised sum. The colour of the filter illuminated by Illuminant C is the original chromaticity with which the calculated set of values (matrix 3) is compared.

It should be remembered that the C.I.E. colour diagram is not a uniform chromaticity diagram (i.e. equal distances on this diagram do not necessarily mean equally distinguishable colours) so that allowance must be made for this feature. A mere quotation of the Δx and Δy values for the difference between the original and reproduced colours would not directly indicate the error. MacAdam[11] has given a formula to enable Δx and Δy to be converted to "just noticeable differences". Thus

$$ds^2 = g_{11}\Delta x^2 + 2g_{12}\Delta x\Delta y + g_{22}\Delta y^2 \qquad (5)$$

where g_{11}, $2g_{12}$ and g_{22} are coefficients which vary over the C.I.E. diagram and which have been plotted[11] and ds is the colour difference in "just noticeable differences" (j.n.d.). One j.n.d. is a rather critical assessment since this corresponds to the minimum discernible difference between two sharply divided and adjacent halves of a bipartite field subtending 2° at the observer. For the present purposes, 10 j.n.d. would seen a more reasonable figure and it is usually in this form that MacAdam's results are plotted.

The results of these calculations for the twelve colours mentioned above are shown on the chromaticity diagram in Fig. 7 and in j.n.d. in Table 2. It will be

*Positive parts of Fig. 1.

**In practice, the outputs must be raised to the power of $\frac{1}{\gamma}$ to compensate for the gamma (γ) of the cathode-ray tubes.

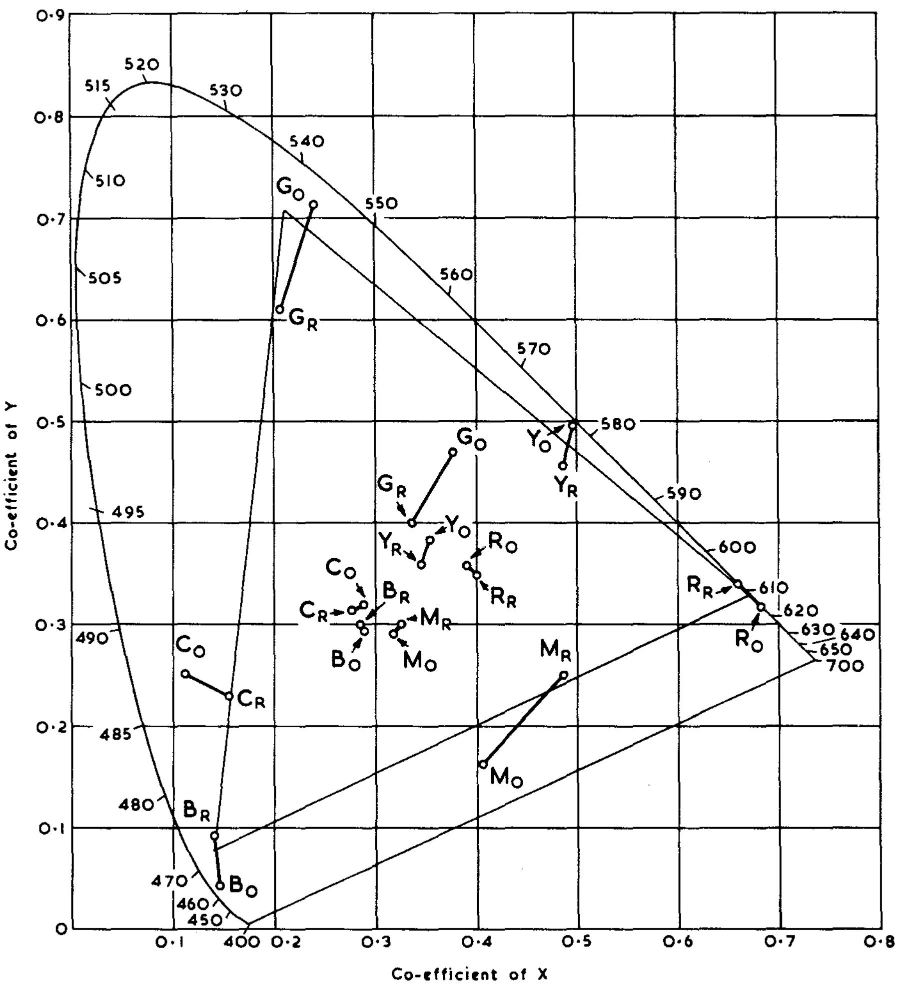

Fig. 7 - Chromaticities of twelve colours as reproduced by a scanner using responses shown in Fig. 6 compared with their original chromaticities

The letters R, G, B, M, Y and C refer to the colours, and the subscripts 0 and R to original and reproduced chromaticities respectively

noticed that all the fully saturated colours are outside the R, G, B triangle formed by the N.T.S.C. primaries so that some error in their reproduction is inevitable. For this reason, the reproduction by the ideal system including negative lobes (Fig. 1) has also been calculated and the results of this are shown in Fig. 8 and Table 3. The desaturated colours are now reproduced with an average error of 1·3 j.n.d., which is the computational error. Table 2 shows that these same desaturated colours were reproduced in the practical case with an average error of 10·2 j.n.d. This is a fairly satisfactory state of affairs, as has been demonstrated by the showing of optically projected duplicate colour slides side by side with a colour television display, which formed part of the demonstration of colour television given to the C.C.I.R. and others. As far as the fully saturated colours are concerned, the mean error for a perfect set of analysis filters is 27·1 j.n.d.: the mean error with the practical system is 37·7 j.n.d. which is just over 10 j.n.d. greater error than the minimum possible for the reproduction primaries selected for the N.T.S.C. colour television system (Table 1). This constitutes a tolerably accurate system of colour reproduction.

TABLE 2

Visible differences between colours as reproduced by a film scanner using shaping filters, and the original colours

Saturated Colours	Visible Difference j.n.d.
Red	25·2
Green	23·3
Blue	71·8
Yellow	17·4
Cyan	29·8
Magenta	58·4

Desaturated Colours	Visible Difference j.n.d.
Red	10·4
Green	21
Blue	5·7
Yellow	10·2
Cyan	7·9
Magenta	5·7

TABLE 3

Visible differences between colours as reproduced by a film scanner having ideal spectral responses including negative lobes, and the original colours

Saturated Colours	Visible Difference j.n.d.
Red	13·5
Green	3·4
Blue	59·4
Yellow	9·4
Cyan	38·2
Magenta	38·5

Desaturated Colours	Visible Difference j.n.d.
Red	2·5
Green	1·9
Blue	0·0
Yellow	1·3
Cyan	1·0
Magenta	1·1

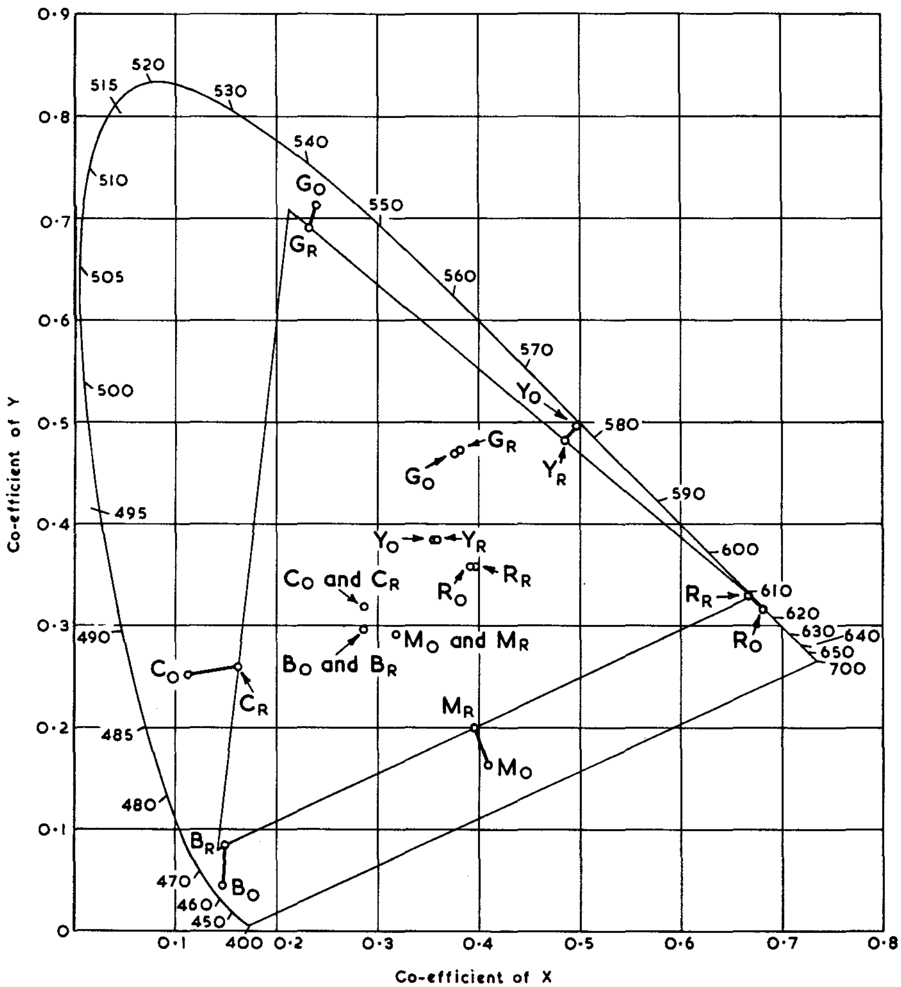

Fig. 8 - Chromaticities of twelve colours as reproduced by a scanner having ideal spectral responses shown in Fig. 1 compared with their original chromaticities

The letters R, G, B, M, Y and C refer to the colours, and the subscripts 0 and R to original and reproduced chromaticities respectively

5. MATRIXING METHODS SIMULATING NEGATIVE SENSITIVITIES.

The ideal analysis system demands negative sensitivities in the colour analysis (Fig. 1). These are difficult to achieve in photography, but are, in principle, not at all difficult for colour television signals, since these can easily be subtracted by means of an electrical matrix. Each major positive lobe (Fig. 1) has two subsidiary lobes which are both negative for the green channel and which are negative and positive for the red and blue channels. If the outputs from the R, G and B channels of the scanner (without the shaping filters) are put into the matrix

$$\begin{bmatrix} R^* \\ G^* \\ B^* \end{bmatrix} = \begin{bmatrix} 1\cdot43 & -0\cdot29 & -0\cdot14 \\ -0\cdot08 & 1\cdot54 & -0\cdot46 \\ 0\cdot00 & -0\cdot54 & 1\cdot54 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{6}$$

then R*, G*, B* are the corrected outputs and R, G, B are the inputs obtained from the flying-spot cathode-ray tube, dichroic mirrors and photocells. The determination of the values in the matrix has been made empirically to secure the best fit and the results are shown in Figs. 9(a), (b) and (c). The criterion by which the success of

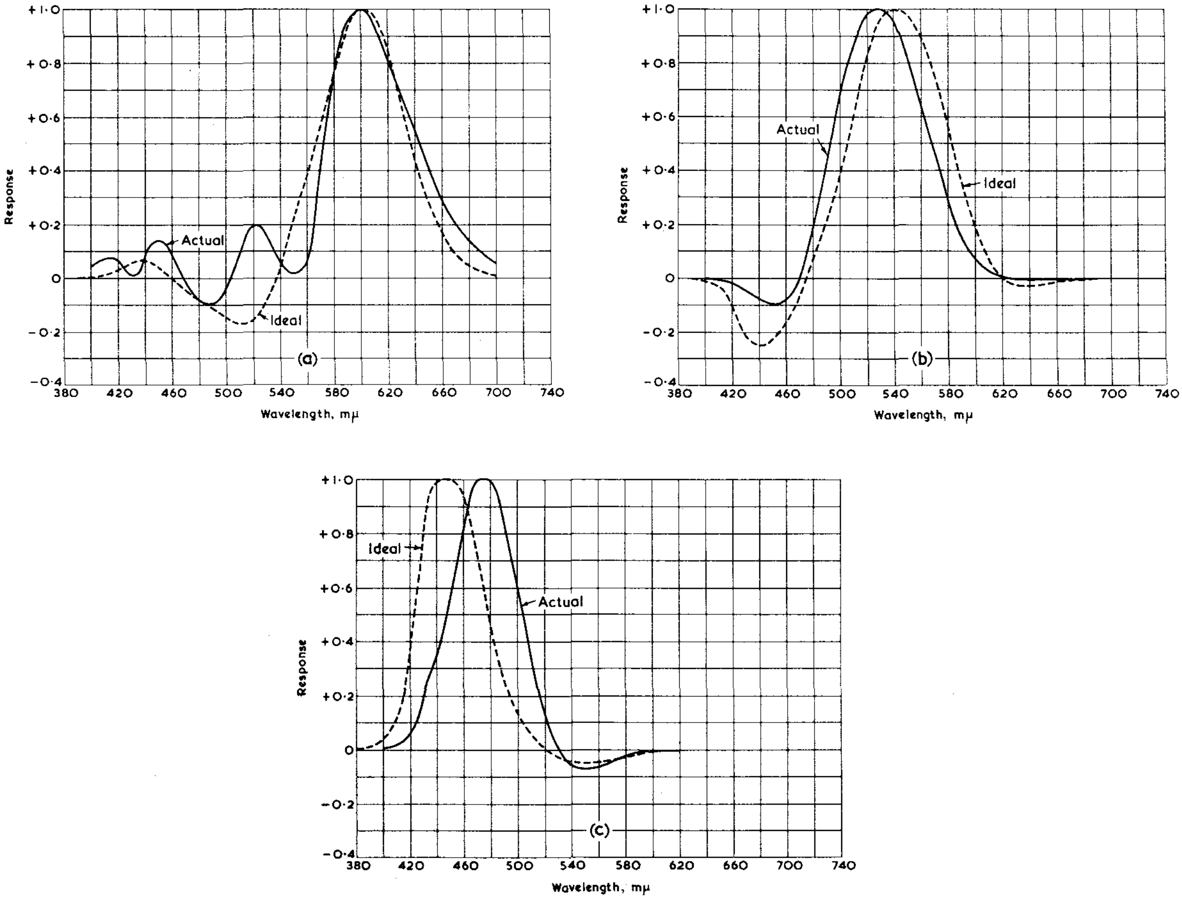

Fig. 9(a) - Response of red channel using matrix 6 on outputs of scanner
(b) - Response of green channel using matrix 6 on outputs of scanner
(c) - Response of blue channel using matrix 6 on outputs of scanner
(without shaping filters)

this scheme must be judged is the accuracy of colour rendering. Fig. 10 and Table 4 give the chromaticities and j.n.d. respectively. The average value of the error in reproduction for the desaturated colours is 7·7 j.n.d., which shows some improvement on the previous value of 10·2 j.n.d., although whether the improvement can be regarded as very significant is doubtful. The fully saturated colours are reproduced with an average error of 34·9 j.n.d.: this is to be compared with an error of 37·7 j.n.d. for the system involving shaping filters. The colour accuracy is thus improved by nearly 3 j.n.d. As the colours are outside the capability of the system, the improvement should be regarded as 3 j.n.d. in 10·6 rather than in the full error. These improvements might be worth while, but a fairly detailed series of subjective appraisals would be required to decide the point.

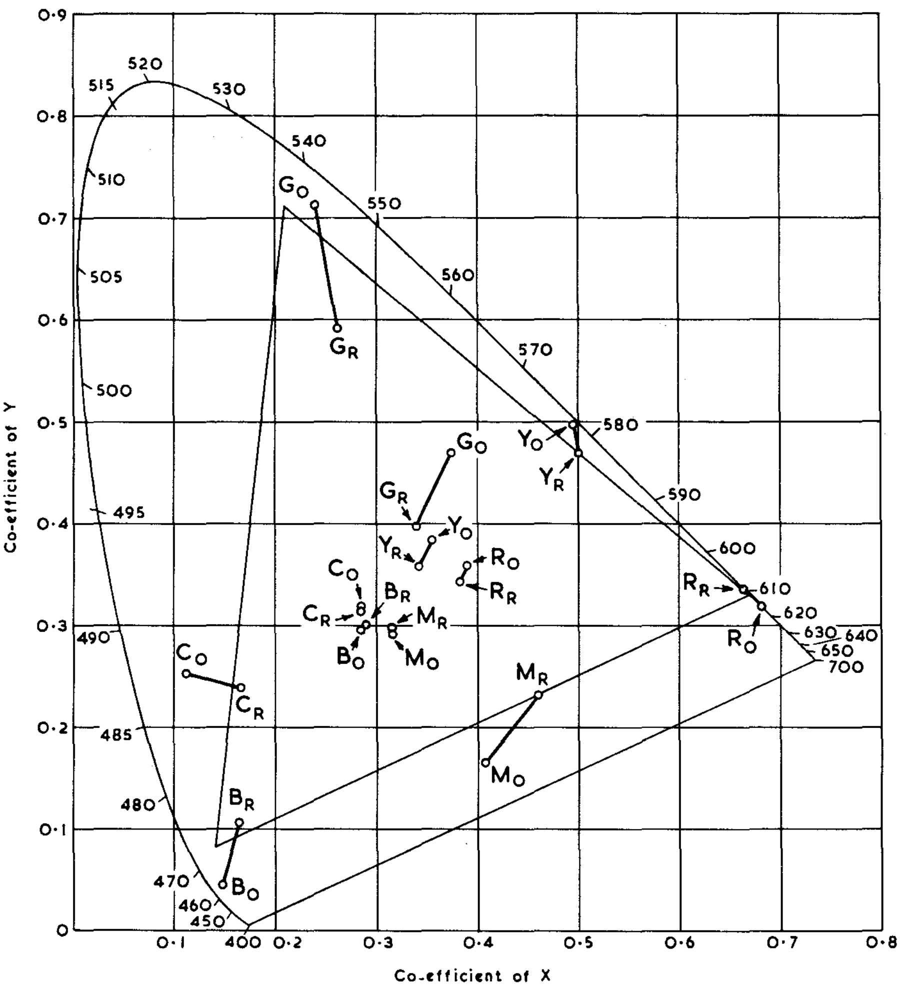

Fig. 10 - Chromaticities of twelve colours as reproduced by a scanner having spectral responses shown in Fig. 9 compared with their original chromaticities

The letters R, G, B, M, Y and C refer to the colours, and the subscripts O and R to original and reproduced chromaticities respectively

Improvements in colour rendering by the use of an electrical matrix are only achieved by some sacrifice in the signal-to-noise ratio of the resulting pictures. Matrix 6 implies that signals are subtracted; the r.m.s. noise associated with the signals will always add, so that although the shaping filters were not used in this second system (and this causes some increase in the signal levels), the subtraction of signals causes a reduction in the signal-to-noise ratio. The two cases have been evaluated and the results are shown in Table 5. From this it can be seen that the signal-to-noise ratio of the red channel is made 2 dB worse and the other two channels 1 dB worse. To date this system has not been instrumented because it is doubtful whether on the existing scanner it is permissible to reduce the signal-to-noise ratio of the red channel. It is barely satisfactory with the shaping filters quoted above and a first requirement of any new system would be to improve the signal-to-noise ratio.

TABLE 4

Visible differences between colours as reproduced by a film scanner having the spectral responses shown in Fig. 9, and the original colours

Saturated Colours	Visible Difference j.n.d.
Red	19·8
Green	16·7
Blue	74·3
Yellow	15·7
Cyan	39·3
Magenta	43·5

Desaturated Colours	Visible Difference j.n.d.
Red	6·9
Green	21·0
Blue	2·7
Yellow	9·7
Cyan	2·3
Magenta	3·8

TABLE 5

Relative signal-to-noise ratios

Method	Channel		
	Red	Green	Blue
1. Shaping filters	0·568	1·04	1·01
2. Electrical matrix	0·449	0·91	0·822
Method 2 – Method 1	–2 dB	–1 dB	–1 dB

6. CONCLUSIONS.

1. The colour accuracy of a scanner using dichroic mirrors and the best available shaping filters has been evaluated and found to be about 10 j.n.d. from perfect reproduction.

2. Some improvement can be achieved by the use of an electrical matrix, but

only by permitting a lower signal-to-noise ratio, particularly in the red channel.

3. The present standard of colour accuracy is considered to be reasonably satisfactory, and efforts to improve it must await signal sources (flying-spot cathode-ray tubes and multiplier photocells) with appreciably better signal-to-noise ratios.

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*This report has not yet been issued.

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